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Fuzzy Sliding Mode Control of a Switched Reluctance Motor

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Abstract

The simplicity, ruggedness, and low cost of a switched reluctance motor (SRM) makes it a viable candidate for various general-purpose adjustable-speed and servo-type applications. Sliding mode control (SMC) is one of the popular strategies to deal with uncertain control systems. The Fuzzy Sliding Mode Controller (FSMC) combines the intelligence of a fuzzy inference system with the sliding mode controller.PI controllers are generally used for the speed control of SRM main drawback of PI controller is high overshoot and large settling time. The main reason for this high overshoot and large settling time is due to the fixed nature of the controller parameters. In this paper, mathematical modelling of 6/4 SRM has been developed, speed performance of the motor using PI controller and FSMC has been analysed.Results of this study show that the overshoot is completely eliminated and the speed of response is improved when Fuzzy SMC is used for the speed control of SRM

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Keywords: Switched Reluctance Motor; PI Controller; Fuzzy Sliding Mode Controller

1. Introduction

The Switched Reluctance Motor (SRM) is an electric motor which runs by reluctance torque. For industrial applications requiring very high speed such as 50,000 rpm, the switched reluctance motor can be used. Switched Reluctance Motors have advantages such as high speed operation, high degree of independence between phases, short end-turn, and low inertia.

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Switched Reluctance Drive (SRD) is a step less speed regulation system, which is composed of SRM, converter and controller. In order to obtain high quality control in either torque or speed control applications, it is essential to have an accurate model of the motor that describes the torque characteristics. The SRM's drive performance is strongly dependent on its design and mostly on its control which allows for torque ripple reduction, or for improving the speed control [1]. Therefore, the motor's mathematical model and its accuracy are important [2][3][4]. SRM linear and nonlinear model with the voltage and hysteresis current control discussed in [5]. A simplified linear model for closed loop control of SRM with PI controller is presented in [6].A high efficiency control of SRM used as the integrated starter generator system for vehicles is mentioned in[7].In [8] Different torque control methods and a torque controller implementation for torque ripple reduction have been explained.

Sliding mode control (SMC) is one of the popular strategies to deal with uncertain control systems [9]. The main feature of SMC is the robustness against parameter variations and external disturbances. SMC has been success fully implemented to control drive systems like DC motor and BLDC motor [10] [11].

Over the past few years, fuzzy set theory [12] has been successfully applied to implementing fuzzy logic controllers (FLC) that express feedback control laws using heuristic knowledge, without knowing parameters of the control plants, for many practical industrial control systems [13]. Fuzzy Logic control is one of the popular strategies to deal with uncertain control systems. Nowadays, the quest for new controllers which provide functionality and guarantee precise performance has led the technology into the field of Fuzzy Logic [14] [15]. New control systems have been developed based mostly in this area of knowledge, control of Induction motors [16], antilock braking systems (ABS) [17], robot path planning [18], among others. Despite this, practical applications involving fuzzy controllers as a proved option to conventional controllers are hard to find.

Combining the intelligence with the sliding mode controller the performance of the sliding mode controller can be improved. This report is focused on the performance comparison of a Fuzzy sliding mode controller with PID controller for the speed control of a PM Synchronous Motor. In this report, mathematical modeling of 6/4 SRM has been developed, speed performance of the motor using PI controller and Fuzzy Sliding Mode Controller (FSMC) has been analysed. And torque ripple reduction methods are proposed without affecting the speed performance characteristics.

Nomenclature

V	Stator Voltage
i	Stator current
R	Stator Resistance
L	Stator inductance
Ψ	Flux linkage
θ	Angular displacement
ω	Angular velocity
T	Torque

2. Mathematical Modelling of SRM

A Switched Reluctance Motor is a singly excited, doubly salient machine in which the electromagnetic torques is developed due to variable reluctance principle. Both stator and rotor has salient poles but only stator carries winding. As in dc motor the SRM has wound field coils for stator windings. However the rotor has no attached coils or magnets. The projecting magnetic poles of salient pole rotor are made of soft magnetic material. When the excitation is given to the stator windings, a force is created by rotor's magnetic reluctance that bid to align the rotor pole with the adjacent stator pole. In order to preserve sequence rotation, the windings of stator pole switches in a sequential manner with the help of electronic control system so that the magnetic field of rotor pole was lead by the stator pole, pulling towards it. The rotor pole is said to be "fully unaligned position" when the rotor pole is equidistant from the two adjacent stator pole. This position is called as maximum magnetic reluctance for the rotor pole. In aligned position the rotor poles are fully aligned with the stator poles, this position is called as minimum reluctance of rotor pole. Figure illustrates the 6:4 SRM drive which consists 6 stator poles and 4 rotor poles.

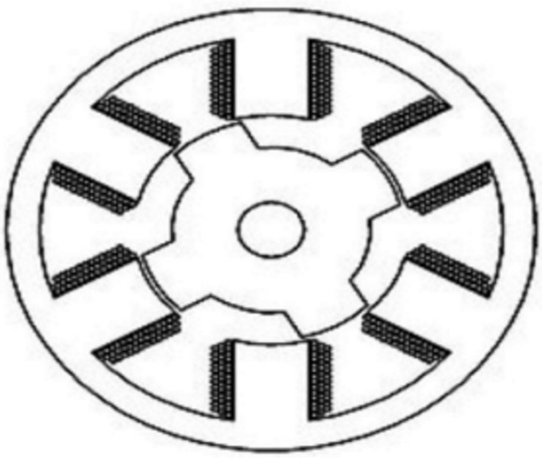

Fig. 1Structure of 3 phase 6/4 SRM.

The equation governing an SRM is given by equation (1) to (5)

$$V = Ri + d\psi/dt \quad (1)$$

$$\psi = Li = N\phi \quad (2)$$

$$V = L\,di/dt + i(dL/d\theta)(d\theta/dt \quad (3)$$

$$V = L\,di/dt + i\omega(dL/d\theta \quad (4)$$

$$T = (1/2)\,i^2(dL/d\theta) \quad (5)$$

This equation determines that the developed torque depends only on current magnitude and dL/dθ direction but it is independent on current direction.

3. Speed control of SRM using PI controller

The Switched Reluctance Motor (SRM) has wound field coils as in a DC motor for the stator windings. The rotor has solid salient-pole rotor (having projecting magnetic poles) made of soft magnetic material. When power is applied to the stator windings, the rotor's magnetic reluctance creates a force that attempts to align the rotor pole with the nearest stator pole. In order to maintain rotation, an electronic control system switches on the windings of successive stator poles in sequence so that the magnetic field of the stator "leads" the rotor pole, pulling it forward.The block diagram of the control scheme of an SRM is given in fig 2.The position of rotor is sensed by the rotor position sensor and it provides its corresponding output to the error detector. Error detector compares reference speed and actual speed to generate error signal which is given to controller block. The controller either fuzzy or PI gives control signal to the converter according to the error signal. The speed of the motor is controlled by the converter through proper excitation of their corresponding windings.

The variation between the set points and the measured variable sets the manipulated variable in the proportional controller. If the variation is high, the manipulated variable will get affected and it cannot stabilize higher order processes. Large gain is needed to improve the steady state error, when proportional controller is used. If proportional gain is high then the system is said to be unstable. If gain is low, it is said to be stable system. Proportional controller does not eliminate the error just reduces it.

The combination of proportional and integral terms is essential to refine the speed of the response and also to eliminate the steady state error. By giving feedback to the converter the performance of the PI controller can be improved and it conquers the disturbances. The forced oscillation and steady state error can be eliminated in PI controller during the operation of P controller and on-off controller respectively.

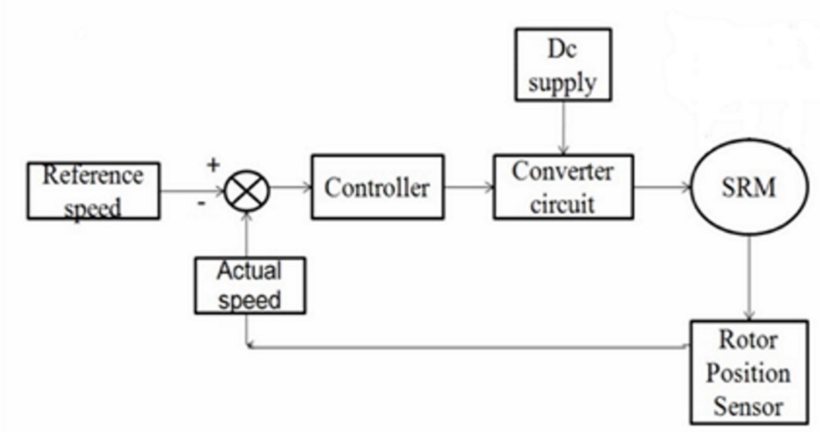

Fig.2 Block diagram of SRM speed control

However, introducing integral mode has a negative effect on stability of the system and in speed response. So that speed response will not increase in PI controller. This problem can be detected by introducing derivative mode. It has the capability to predict the errors and to decrease the reaction time of the controller. If the speed response is not a criteria normally PI controllers are used. The tuning of PI controller is tuned using Ziegler-Nichols tuning method

4. Fuzzy Sliding Mode Control

Sliding mode control is a non-linear control technique and intelligence can be added to this controller by combining the fuzzy logic to the conventional sliding mode control

4.1 Sliding mode control

Sliding mode control (SMC) has a proved history of its performance. The design of SMC is simple and it is robust against variation in process dynamics and external disturbances.

A Sliding Mode Controller is a discontinuous controller and is also known as a Variable Structure Controller (VSC). In a VSC there are several subsystems and switching between these subsystems are done in order to bring the plant states to a user defined surface called sliding surface. Usually the switching among the subsystems is determined by using a switching function. The basic control law of the sliding mode controller is given by:

$$u = -k sign(s) \qquad (6)$$

where *s* is the switching function, *k* is a constant parameter and *sign (·)* is the sign function.

The main disadvantage in conventional SMC is chattering, which is a phenomenon of high frequency oscillation in the output, due to the high frequency switching between the functions. Chattering adversely affects the performance of the system significantly. Using a signum function often causes chattering in the system. One of the solutions to overcome this is to introduce a boundary layer around the switching surface. The chattering in the sliding mode controller can be reduced by modifying the control law in as $u = -k sat(s/\phi)$ and constant factor ϕ defines the thickness of the boundary layer around the switching surface. $sat(s/\phi)$ is a saturation function that is defined as

$$sat(s/\phi) = \begin{cases} \dfrac{s}{\phi} & if \left|\dfrac{s}{\phi}\right| \le 1 \\ \operatorname{sgn}(s/\phi) & if \left|\dfrac{s}{\phi}\right| > 1 \end{cases} \qquad (7)$$

The above control law guarantees the system trajectories move toward and stay on the sliding surface $s = 0$ from any initial condition, if the following condition is satisfied:

$$s\dot{s} \le -\eta|s| \quad (8)$$

where η is a positive constant that makes the system trajectories meet the sliding surface in a finite time. The value of ϕ is taken as unity. The above controller is actually a continuous approximation of an ideal relay control. The invariance of sliding mode control is eliminated using this control scheme. The system robustness is become as a function of the width of the boundary layer. The control law of SMC of a plant of any order reduces the error and the derivative of error to zero. The switching surface of the SMC determines the transient response of the system if the sliding mode exists. The error in the rotor speed of the machine is used to generate the switching surface and is given by

$$e(k) = \omega_{ref}(k) - \omega(k) \quad (9)$$

where, $\omega(k)$ and $\omega_{ref}(k)$ are the actual speed and the desired reference speed respectively and $e(k)$ and k are the error in speed and the sampling interval respectively. The sliding surface (s) is defined with the tracking error e, its rate of change of $\dot{e}$ and its integral ($\int edt$). The sliding surface is given by

$$s = \dot{e} + \lambda_1 e + \lambda_2 \int edt \quad (10)$$

where $\lambda_1$and λ_2 surface parameters. The values of $\lambda_1$and λ_2 determine the slope of the sliding surface and one of the conditions for the existence of sliding surface is that $\lambda_1$and λ_2 are strictly positive real constants. The values of $\lambda_1$and λ_2 are selected by using trial and error so that the surface has a positive slope. Also these values should satisfy equation (8). Hence the values of $\lambda_1$and λ_2 are selected as 10 and 20 respectively which are strictly positive and satisfies the equation

.4.2 Fuzzy Sliding Mode Control

Control law of SMC is $u = -ksign(s)$ given by eqn (6). The performance of the sliding mode controller can be improved if the constant k in the control law is intelligently varied according to the variation in the error signal and the rate of change of error signal. The sliding surface signal s and its rate of change $\dot{s}$ are taken as the input to the fuzzy system and the value of k is the output of the fuzzy system.

The input membership function for s and $\dot{s}$ are given in fig.3and fig.4 respectively. Triangular membership functions are used and the universe of disclosure is taken as -50 to 50 for s and -10 to 10 for ds/dt. The output membership function is given in fig.5. Triangular and trapezoidal membership functions are used as output membership functions for de-fuzzification and the universe of disclosure is taken as and 0.5 to 1.5. The fuzzy rules are given in in table 1.

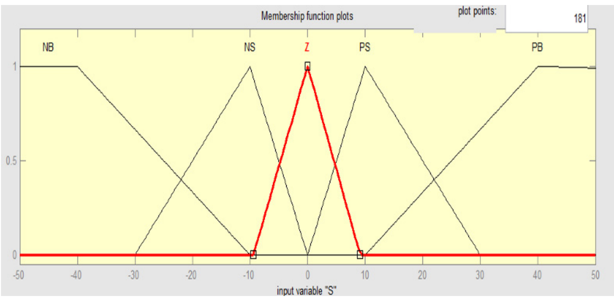

Fig.3 Input membership function s

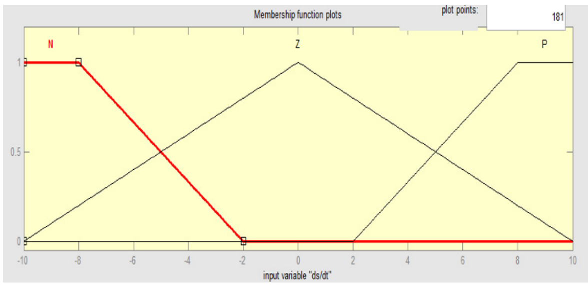

Fig.4 Input membership function s dot

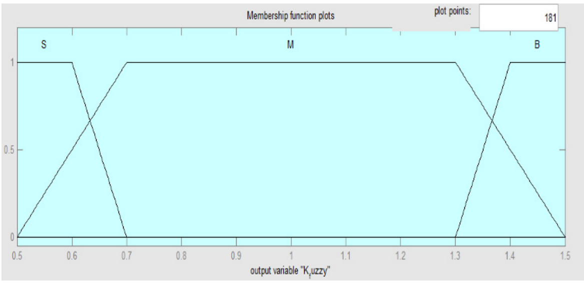

Fig .5 Output membership function K fuzzy

Table1. Fuzzy Rules

S / *sdot*	***NB***	***NS***	***Z***	***PS***	***PB***
N	B	M	M	S	B
Z	B	M	S	M	B
P	B	S	M	M	B

5. Results & Discussions

The Fuzzy Sliding Mode Controller for the speed control of SRM is implemented in MATLAB/Simulink and the results are compared with that of a conventional PI Controller. The simulation is conducted on a 3.6 KW SRM whose parameters are given in table 2

The Simulink block diagram for the speed control of SRM using Fuzzy SMC controller is shown in fig 6. The sensing of rotor position is essential for implementing an appropriate technique for the speed control of SRM. By sensing the speed of the motor, the rotor position is estimated.

The system is simulated using fuzzy sliding mode controller with triangular membership functions first. Then system with PI controller is simulated for the values of K_p and K_i, which are obtained from Ziegler- Nichols tuning method.Fig.7 shows the step response of the system with fuzzy SMC and conventional PI controller for a reference speed of 2000 rpm. A load torque of 20 Nm is applied at 0.2 seconds after starting. Fig 8 shows the enlarged view of the step response near 2000 rpm. The performance comparison is given in table 3. It is observed that the rise time with proper tuning of PI controller is 0.1 sec which is reduced to 0.025 sec with FSMC. The peak overshoot and steady state error are completely eliminated with FSMC which are19.8% and 2% respectively with PI controller. Moreover the settling time of 2 sec with PI controller is reduced to 0.1 sec with FSMC. The speed variation while loading was also improved to 0.5% with FSMC from 2.25% with PI controller. From the results it is clear that a fuzzy sliding mode controller can perform better than that of a conventional PI controller in terms of rise time, overshoot, settling time and steady state error. Also the speed variation while loading is low with Fuzzy sliding mode control compared to conventional PI controller.

Table 2 Motor Parameters

Rated Power	**3.6KW**
Rated phase to phase voltage	240V
Rated current	15A
Rated speed	2000 rpm
No of stator poles	6
Stator Resistance (R)	0.01ohm
Stator inductance	0.00067 H
Maximum flux linkage (ψ_m)	0.486 wb
Moment of inertia (J)	0.0082
Viscous friction coefficient (B)	0.01

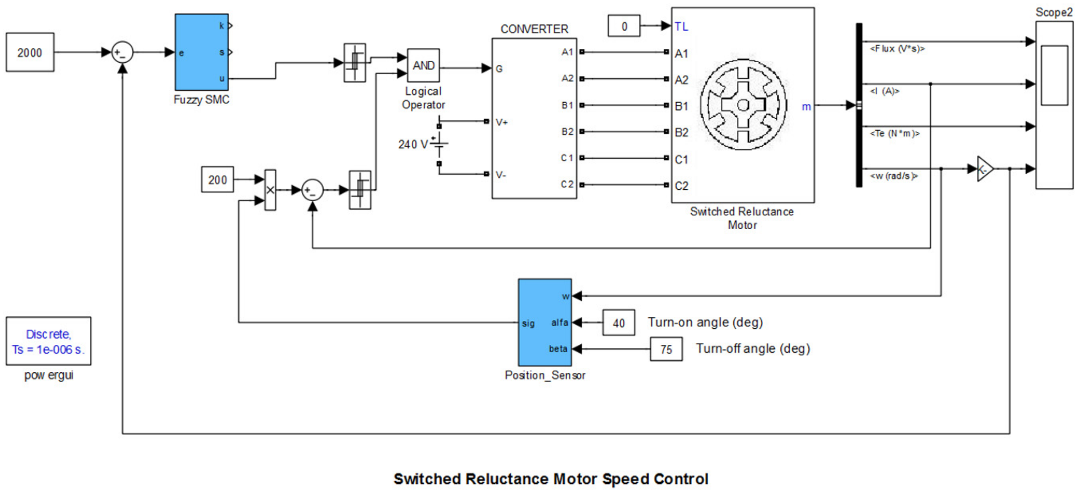

Fig.6. Simulink Block diagram of SRM with Fuzzy Sliding mode controller

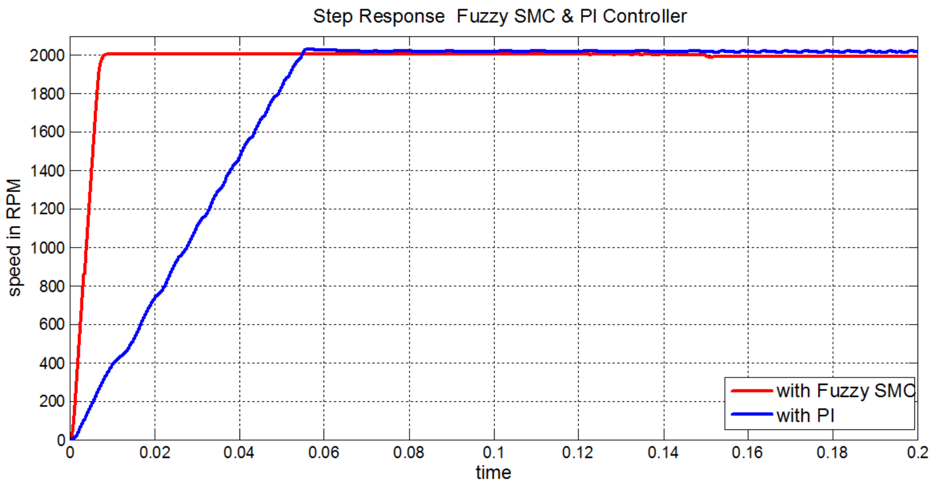

Fig.7 Step response with Fuzzy SMC and PI controllers

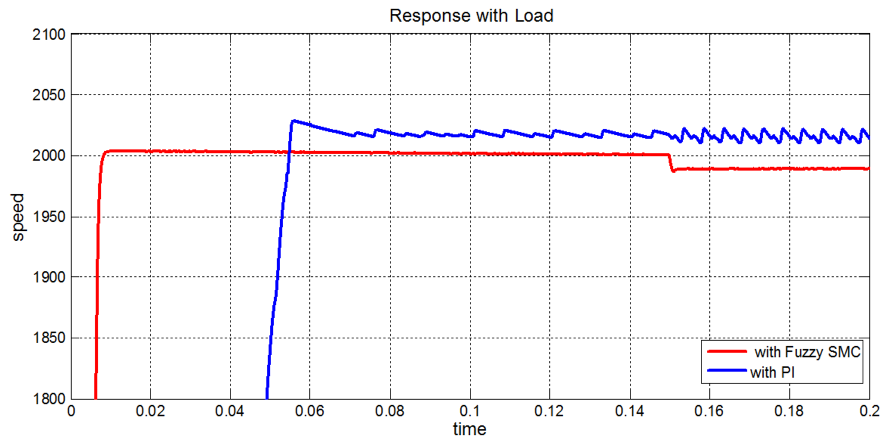

Fig.8 Response while loading with Fuzzy SMC and PI controllers

Table 3 Performance comparison

	PI	Fuzzy SMC
Rise time	0.1sce	0.025 sec
Peak overshoot	19.8%	0%
Settling time	2 sec	0.1 sec
Steady State error	2%	0%
Speed variation with load of 20Nm	2.25%	0.5%

6. Conclusion

Performance comparison of the speed control of Switched Reluctance Motor with fuzzy sliding mode controller and conventional PI controller is carried out in this paper. The PI controllers give moderate performance under undisturbed conditions even though they are very simple to design and easy to implement. But their performance is poor under disturbed condition like sudden changes in reference speed and sudden change in load. The SRM with PI controller shows large overshoot, high settling time and comparatively large speed variation under loaded condition.

The Fuzzy Sliding Mode Controller combines the intelligence of fuzzy logic with the Sliding Mode technique. The peak overshoot is completely eliminated and the rise time and settling time is improved when Fuzzy SMC is used for the speed control of SRM. The speed variation of the motor under loaded condition is reduced when fuzzy SMC is applied.

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